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DESIGN OF A RADIO FREQUENCY DATA LINK FOR THE UNMANNED GROUND VEHICLE TECHNOLOGY TEST BED DEMONSTRATION PROGRAM

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A description of the design of an L-Band Radio Frequency data link for the Unmanned Ground Vehicle Technology Test Bed Program conducted by Research, Development, and Engineering Center, MICOM is presented. This report describes the command and control data link design. The system provides remote operator control communications for a robotic HMMWV. The data link utilizes a bidirectional RF system with a relay station to provide non-line-of-sight operations. The report details the design and expected performance of the data link.

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I. SYSTEM REQUIREMENTS

The Advanced Sensors Directorate, Millimeter/Microwave Guidance Technology Branch in support of the Unmanned Ground Vehicle (UGV) Technology Test Bed (TTB) Demonstration Program has designed and is developing a Radio Frequency (RF) data link for the TTB. The RF data link will provide the primary means of communicating and controlling a HMMWV based remotely controlled vehicle. The purpose of this report is to describe the data link design being developed.

The system requirements for remote operation of the TTB are to provide a system that performs the following operations:

1. self transportable on the battlefield,
2. teleoperated remote vehicle via an RF data link or a Fiber Optic (FO) link for special applications,
3. to remotely conduct a reconnaissance mission in a vehicle parked status. This includes to search, detect, recognize, identify, and locate vehicle type targets during day or night, and in all weather.

To accomplish the above system requirements, the RF data link requires the capability to transmit from the Operator Control Unit (OCU) to the Mobile Base Unit (MBU) command information. It also requires the capability to transmit from the MBU to the OCU video sensor imagery, acoustic sensor data, and vehicle/system status information. Finally, it is required to provide voice communications in both directions. In order that the MBU be remotely teleoperated and self transportable, it is required that video imagery be provided in real time to permit vehicle mobility. Finally, the desired range of operations from OCU to MBU is six kilometers point to point which places the requirement for Non–Line–of–Sight (NLOS) operations.

Derived requirements for the UGV TTB data link were determined from review of the Surrogate Teleoperated Vehicle data link, UGV documents, and experience recommendations of program personnel. The worst case link route was estimated. It assumes that the OCU will be located at about the same elevation as the MBU but both visual and radio paths are separated by obstructions, such as a mountain, building, or dense tree line. For this condition the path must have a repeater station at some higher elevation in view of the OCU and MBU simultaneously. A further requirement is that there should be no azimuth orientation restriction of either vehicle. Also, all vehicle antennas must be short, tough in design and unlikely to be damaged by overhanging limbs. A highly desirable feature is that the link be transparent to the OCU and MBU interface computers and operator.

Derived operational requirements for the TTB are summarized in Table 1. The conceptual operational approach is shown in Figure 1. Signal Flow requirements are shown in Figure 2.

Table 1. RF Data Link Operating Requirements

Visual Data	Two return television links (stereo). NTSC compatible (4.2 MHz bandwidth).
Serial Data	A full–duplex, RS–233 serial link will be provided between the OCU and MBU. Maximum information transfer rate will be 38.4 k/Baud. Error rate from random noise is to less than one bit error in 10^5.
Forward Audio	One forward audio link with a frequency response of 300 Hz to 3 kHz.
Return Audio	Two return audio links with a frequency response from 20 Hz to 16 kHz ± 1.5 dB. Weighted signal to noise (S/N) will be a minimum of 50 dB.
Directivity	Continuous communications required for any location or position of UGV.
Repeaters	Repeaters on towers are to enable communications for NLOS operations to six kilometers.

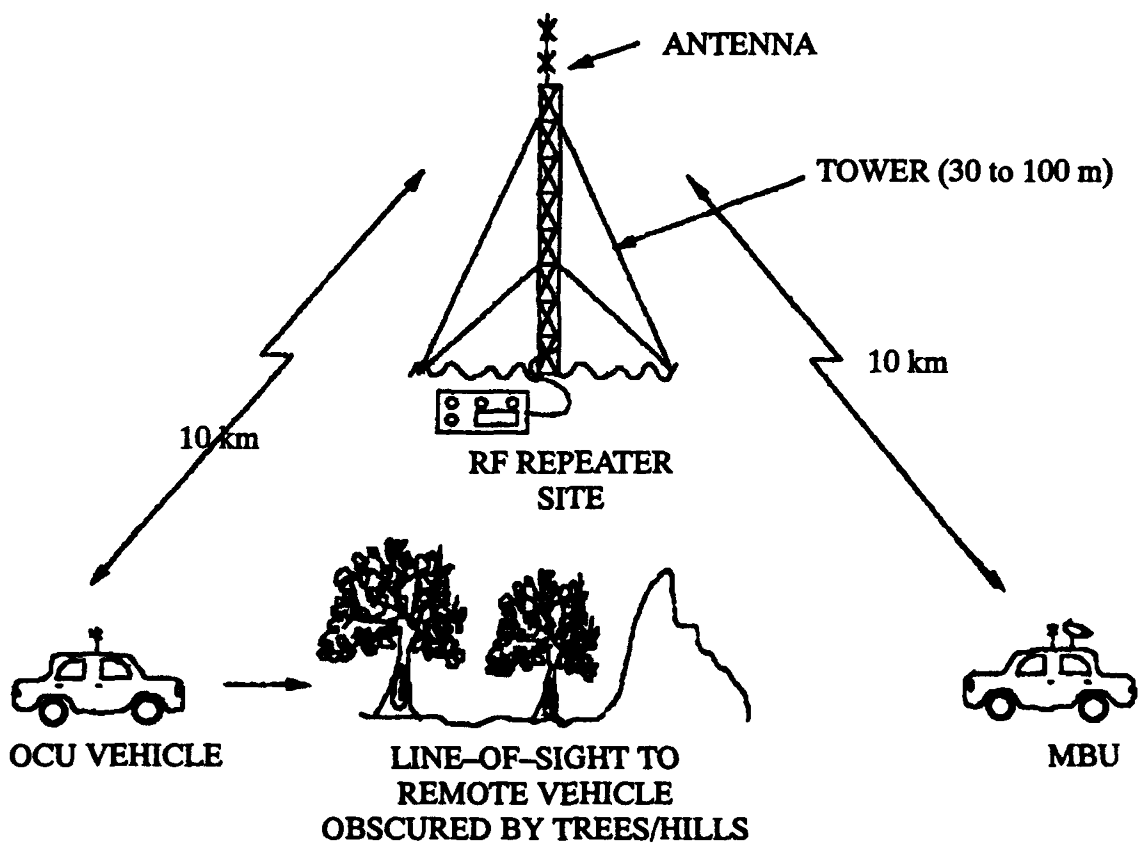


Figure 1. TTB Data Link Conceptual Approach

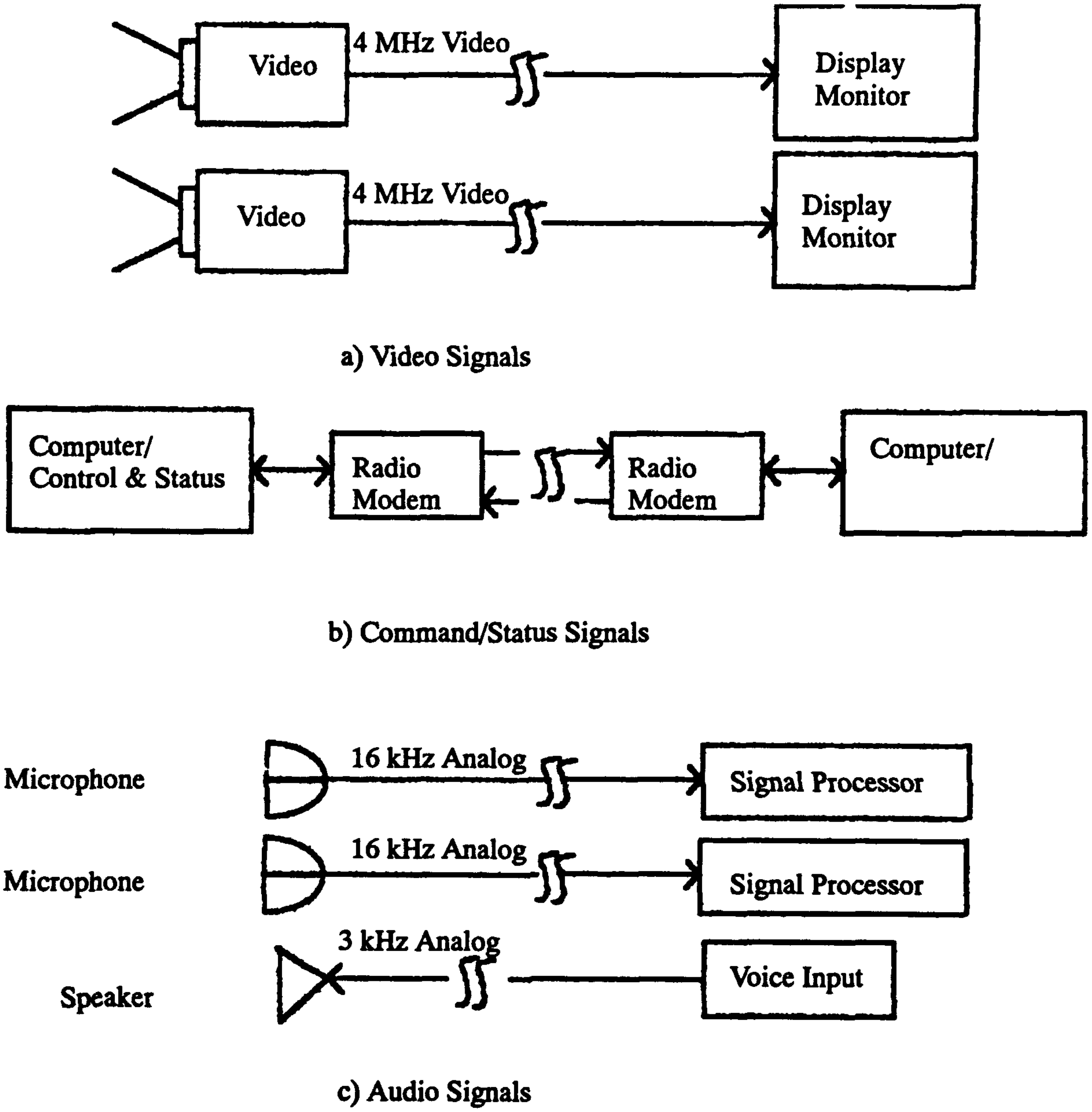


Figure 2. TTB Data Link Signal Flow

II. TECHNICAL APPROACH

A. Design Considerations

The initial criteria imposing limitations on the development of an RF data link were (1) the use of available commercial assets, and (2) the use of off–the–shelf military hardware. The hardware availability of both these avenues was evaluated. For the use of available commercial assets, the primary limiting factor was that the available radios were fixed frequency and not at available frequencies for Redstone Arsenal. The use of military radios provided tunable frequency but limited the digital data rate to 4800 baud and required an external multiplexer to achieve the required data rate of 9600 baud, or the growth rate of 38.4 kilobaud. Further, video was not considered practicable unless the imagery was digitized and some form of image compression was available. Finally the physical size, weight, and power were excessive for the available space in the HMMWV. Therefore, the use of commercial, off–the–shelf, radio hardware hardened for missile–type flight was investigated. This option proved the only viable one.

B. Design Approach

An analog radio transmission system is recommended for the UGV Data link. An all digital approach was considered, but discarded since the link is considered interim for UGV development. Cost was also a major reason since current video link designs that carry television, audio, and data in an analog format are well understood, reliable and available.

The basic return (MBU to OCU) link design is based on the use of broad bandwidth frequency modulated (FM) transmitters that will carry the video signal as a direct baseband modulation. Data will be carried on the same channel as two high frequency (6.8 and 8.2 MHz) FM modulated subcarrier oscillators. The receiver end will use a conventional FM receiver with two subcarrier discriminators to decode the data channel information. Mutual interference between the video and data channels will be prevented by using a 4.2 MHz low pass filter to isolate the video from the data channels and bands filters of approximately 1 MHz bandwidth to provide subcarrier isolation. The return video links will be transmitted at L–Band, while the forward command link will be received at S–Band.

A substantial Signal to Noise (S/N) improvement will be obtained in the video channel to provide excellent television pictures of low noise. Minimum Carrier to Noise (C/N) ratios will be as low as 22 dB. Through the use of pre–emphasis and de–emphasis, a high index modulation, and signal weighting a demodulated video S/N of 41 dB may be obtained.

The forward (OCU to MBU) link will command data consisting of narrow band serial data and one channel of voice quality audio. The link concept is similar to the return video links except that only one subcarrier is used for the audio data and the serial data is directly baseband FM modulated onto the RF carrier. In turn, the receiver on the MBU will be narrow band with only one discriminator. The forward link will be transmitted at L–Band, and the return video links will be received at S–Band.

A repeater, located on an elevated site, will relay the signal to and from each vehicle. The repeaters will amplify the L–Band video signal received from the MBU, and up–convert to S–Band for retransmission to the OCU, and will amplify the received L–Band command signal from the OCU, and up–convert to S–Band for retransmission to the MBU. The repeater design is to be of the non–demodulating type. This type of repeater does not demodulate to baseband and remodulate the signal for retransmission, rather the signal always remains in the modulated RF format.

1. Range Performance Considerations

Several factors affect range performance of an RF data link. These include antenna height, vegetation losses, video, audio, and data performance requirements, data channel performance and frequency availability.

a. Antenna Height

To achieve the nominal required range of 6 kilometers and goal of 10 kilometers the elevation of antenna is a crucial factor. On a HMMWV the typical antenna height is 1.8 meters (6.6 feet). The radio horizon is determined by the Equation (1)

$$R = \sqrt{2 * H_t * H_r} \tag{1}$$

where R is range, H_t is the height of transmit antenna, and H_r = height of receive antenna.

Using Equation (1), the estimate radio horizon was determined to be:

Ht (ft)	Hr (ft)	Range (mi)	Range (km)
6.6	6.6	9.3	15

which is more than adequate for this task. However, the TTB is a ground–to–ground vehicle based system. At the available frequencies which are Line–of–Sight (LOS) frequencies, factors such as terrain contour, vegetation, and buildings become a factor. These can effectively block the LOS between the transmitter and receiver.

In order to alleviate the blocked LOS, the use of an elevated relay station was considered appropriate. A 35 foot mast is available for use. Using Equation (1), the radio horizon was determined again.

Ht (ft)	Hr (ft)	Range (mi)	Range (km)
6.6	35	21.5	34.6
35	6.6	21.5	34.6

Thus, the vehicles are expected to be capable of communicating distances between 15 and 35 kilometers with the proper transmitter and receiver configuration.

Taking consideration of the test area designated for use makes a considerable difference in the expected range of operation. Two areas have been considered for use. Figures 3 and 4 show each potential test site for the TTB at Redstone. Figure 3, the TA–5 area site, consists of rolling hills (30 ft elevation change), some trees, and potentially shallow stream crossings with a drop off of six feet. The relay location is on the shoulder of a hill at an approximate elevation of +200 feet from the test track area. For this location, only the lower SE corner of the site presents a significant NLOS area.

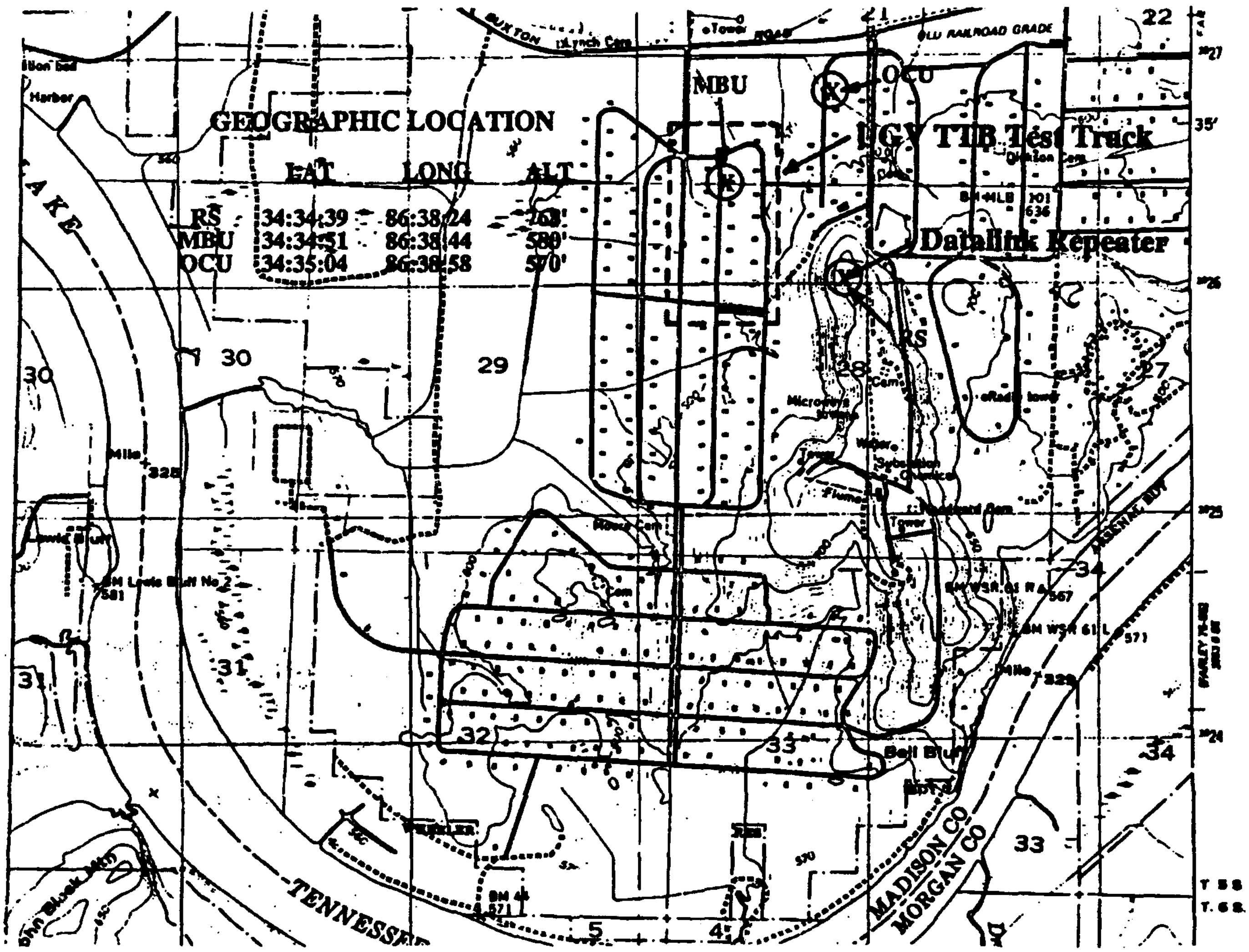


Figure 3. Potential TTB Test Site: TA–5

For Figure 4, a pasture area Northwest of the Redstone airfield, two different circumstances are notable. The first is a long slope of about 50 feet elevation change making up the southern area of the site. LOS here is easily achieved, even though there are scattered stands of trees. The second area is the northern portion which has rolling hills with approximately 100 feet elevation differences. For this area the elevated relay is necessary to achieve LOS. The relay will need to be elevated to 100 feet to achieve LOS in the hilly area. At this time, no location has been designated as a relay site.

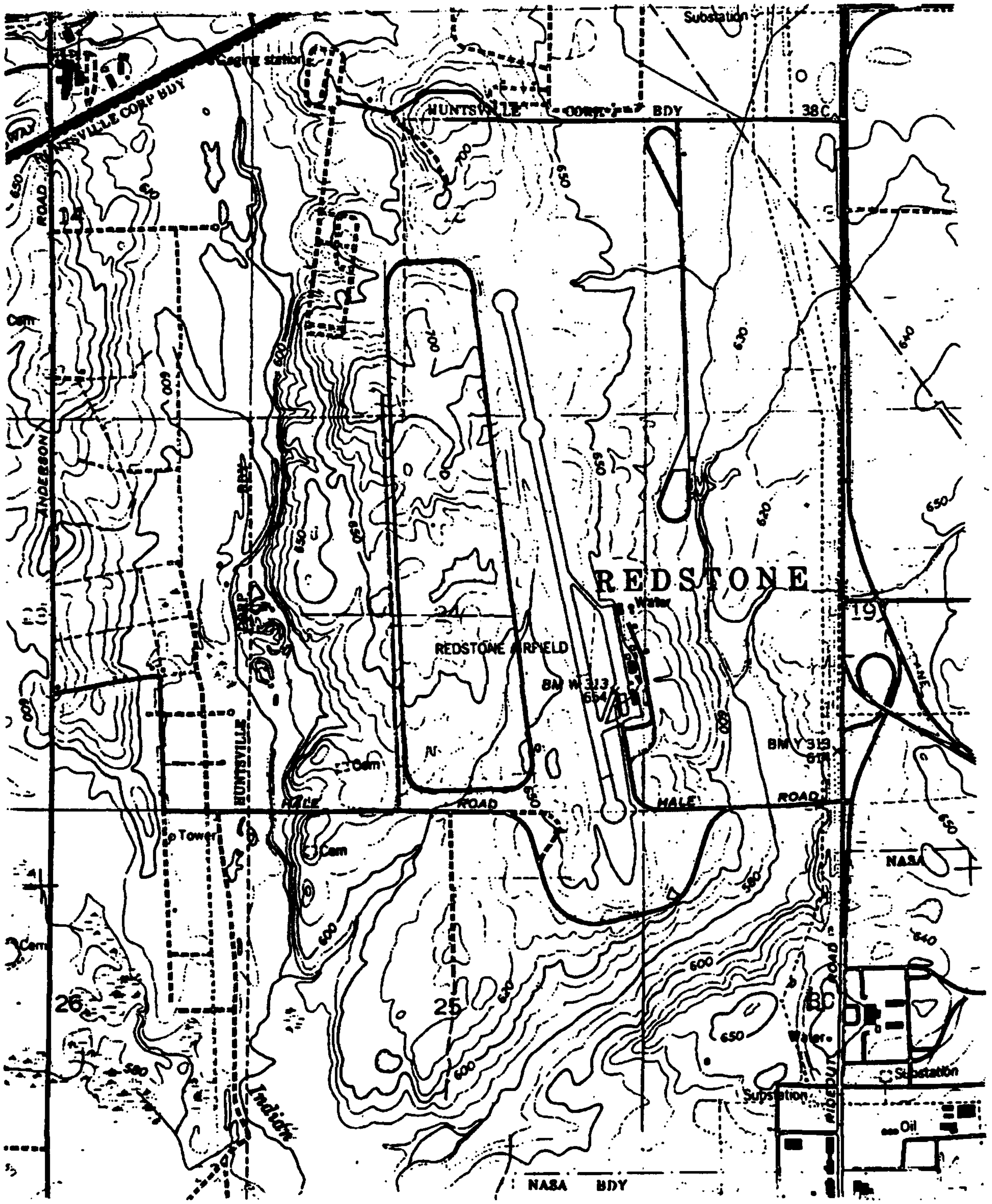


Figure 4. Potential TTB Test Site: Pastures West of Redstone Airfield

b. Foliage Losses

Vegetation effects microwave transmission in two ways. These are absorption and multipath. At the L and S bands both affects are seen. In recent research, Vogel and Hong [2] evaluated both conditions at a frequencies covering L band. Their analysis, based on providing a satisfactory signal level 99 percent of the time, indicated that losses due to vegetation would be approximated as 3 db for farm/prairie land, 8 dB for forest/farm land, and 19 dB for forest lands. Based on the results of such analysis, a value of 10 dB is used as an average value for estimation of losses due to vegetation for this design.

2. Video, Audio and Data Performance

Remote operation of the MBU requires that the operator have a visual image of the terrain. The image must be of good quality, free of noise, and of true color. The EIA/TIA-250-C Standard for Television Transmission System, which covers both video and audio performance will be used, with minor modifications, as a guide for design and test of the data link.

Experiments have been made to relate the performance of a video transmission link to the viewer image quality. The November 1982 issue of the proceedings of the Institute of Electrical and Electronic Engineers [3] published the results of a detailed study of degraded television as it effects the viewer. They concluded that a TV image with noise can be specified as:

Picture Quality	Signal-to-Noise Ratio*
Excellent	greater than 41 dB
Fine	33 to 41 dB
Passable	28 to 33 dB
Marginal	23 to 28 dB
Inferior	17 to 23 dB
Unusable	less than 17 dB

* Video S/N is specified as Peak Video divided by RMS noise using CCIR defined filters.

With the NTSC type of color transmission the luminance channel is defined to have a bandwidth of 4.2 MHz and carry the monochrome gray scale video information. The instantaneous color of a picture element is contained in the phase difference between the element phase and a 3.58 MHz subcarrier. The color hue (intensity) is contained in the instantaneous amplitude of the subcarrier at the picture element. For a short transmission range as anticipated for the UGV TTB the following phase and amplitude performance is recommended:

Minimum video weighted S/N	41 dB
Amplitude response	60 Hz to 4 MHz, ± 1.5 dB
Color differential phase	< 1 degree
Color differential gain	< 1 dB
Input/out level	1 V P-P, including sync.
System impedence	75 ohm
Low frequency bounce	< .5 dB, after DC restoration
Cross talk from data channels	>45 dB isolation

3. Data Channel Performance

Data channels encompass both the forward data (serial) and audio channel (voice quality) and the return data and high quality voice channels. For practicality of link design all of these channels will have basic bandwidths of 100 kHz. Low pass filters will be used to limit bandwidth and noise energy as required. Digital data transmission at an error rate of one error in 10^5 bits will need S/N of about 12 dB. The design of the basic 100 kHz channel will exceed a S/N of > 30 dB. The minimum data rate for the serial channel is 9600 baud as used in the STV. To accommodate possible data capacity growth the basic serial channel will be designed for 38.4 kilobaud. This will allow more time for repeating corrupted data and still meet the original 9600 baud goal. A conventional four wire (two for forward transmission and two for return) modem will be used. The following characteristics are recommended for the data channel:

Forward audio (1 ch)	300 to 3000 Hz + 2 dB, weighted S/N>45 dB, voice grade
Return audio (2 ch)	20 Hz to 16 kHz + 1.5 dB, weighted S/N>60 dB
Forward serial data	38.4 kB/s, analog channel S/N>14.2 dB for BER of 10^{-6}
Return serial data	38.4 kB/s, analog channel S/N>14.2 dB for BER of 10^{-6}

4. Frequency Allocation

The RF frequency for the data link is driven by the need of very wide channel bands (20 MHz) and practical availability of spectrum space at Redstone Arsenal. Discussions with the MICOM Frequency Manager revealed that the available channels with wide bandwidths are in the upper L–Band 1710 to 1850 MHz and S–Band 2310 to 2390 MHz. To operate two independent UGVs will require four video and two data channels. Since the data link concept also uses a repeater where a channel is received on one frequency and repeated at another, this automatically doubles the number of required channels to eight video and four data.

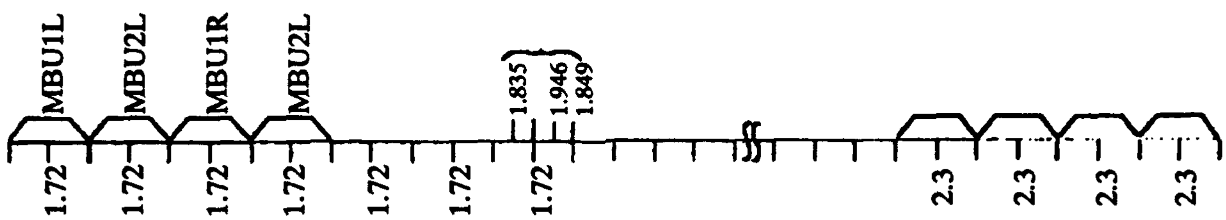
A 4 MHz television video link with a modulation index between 1 and 1.4 will require, as a minimum, two upper and two lower spectral components for a total of 16 MHz. The data subcarriers superimposed on the same carrier will require, using a low index at least for the first upper and lower sideband, 13.6 and 16.4 MHz for 6.8 and 8.2 MHz subcarriers. This will place a practical lower limit of frequency separation of two video links of 20 MHz (including a noise guard band) of ± 1.5 MHz when subcarrier modulation is factored in. To avoid the risk of splash–over between channels, the frequency plan spaces each video channel every 20 MHz and assigns alternate channels to the same UGV thus allowing a 40 MHz guard band between channels of the same UGV. The data only transmitters will be operated in the L–Band and require only 1 MHz bandwidth channel and are spaced 3 MHz apart on a vehicle, allowing a 1 MHz guard band. Closer spacing can be achieved; however, because of the complex modulation scheme, unexpected spill–over interference may be experienced. The chance of interference will be sharply reduced by using bands filters on the transmitter outputs and receiver inputs. For the UGV TTB such very close spacing will not be used. The video/data transmitters chosen for use in this system are FM baseband modulated with a TV signal and have two FM subcarrier oscillators (at 6.8 and 8.2 MHz) that are modulated with serial data or voice.

Video and data transmitting frequencies, bandwidth, and transmitter power for each OCU/Relay/MBU system are listed in Table 2. The frequencies chosen for use are shown for a conceptual two UGV system operating simultaneously. That is two OCU and two MBU coupled with six supporting repeaters. Any of the MBU video transmitters may be changed in frequency in 10 MHz steps starting at 1720 MHz and up, any of the OCU serial data transmitters may be changed in frequency in 1 MHz steps starting at 1835 MHz and up. The same arrangement applies to the repeaters, however they transmit in the S–Band. Figure 5 shows graphically the proposed channels and the allocation of frequencies for the two TTB systems to be built.

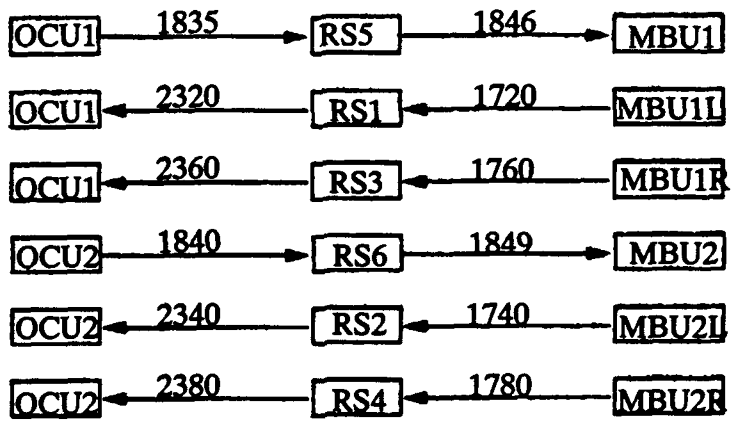
Table 2. Video and Data Channel Frequency Data

F_c (MHz)	P_t (W)	Location	Data Bandwidth (MHz)	RF Bandwidth (MHz)
Video/Data Transmitters				
1720	5	MBU1L	8.2	20
1740	5	MBU2L	8.2	20
1760	5	MBU1R	8.2	20
1780	5	MBU2R	8.2	20
2320	5	RS1	8.2	20
2340	5	RS2	8.2	20
2360	5	RS1	8.2	20
2380	5	RS2	8.2	20
Data Only Transmitters				
1835	5	OCU1	0.1	0.8
1840	5	RS1	0.1	0.8
1846	5	OCU2	0.1	0.8
1849	5	RS2	0.1	0.8

Note: 1. MBU1L = MBU #1, Left Camera, MBU1R = MBU #1, Right Camera.
2. RS1 = Relay System #1, RS2 = Relay System #2.



Spectral Frequency Separation



System Frequency Layout

Figure 5. Frequency Allocations for the UGV TTB Systems

Determination of the required bandwidth was made using Carson's Rule [4]. Carson's Rule is

$$Bn = 2 * (f_p + f_m) \tag{3}$$

where f_p is the highest modulating baseband frequency, and f_m is the peak FM deviation.

Using Equation (3) for the wideband video which has $f_p = 4$ MHz and $f_m = 4$ MHz:

$$Bn = 2 * (f_p + f_m) = 2 * (4 + 4) = 16 \text{ MHz}$$

Including the subcarrier at 8.2 MHz on the video channel, with $f_p = 1.6$ MHz and $f_m = 8.2$ MHz:

$$Bn = 2 * (f_p + f_m) = 2 * (1.6 + 8.2) = 19.6 \text{ MHz}$$

Total bandwidth for the video transmission with subcarriers is approximately 20 MHz.

Using Equation (3) to calculate the bandwidth required for the narrowband serial data (the uplink command channel), we find, using $f_p = 300$ kHz and $f_m = 100$ kHz the bandwidth required is:

$$Bn = 2*(f_p + f_m) = 2*(0.3 + 0.1) = 0.8 \text{ MHz}$$

The subcarrier on the data channel is at 0.4 MHz. This requires a bandwidth of

$$Bn = 2*(f_p + f_m) = 2*(0.4 + 0.1) = 1.0 \text{ MHz}$$

Therefore, the total required command link bandwidth is 1.0 MHz.

III. DESIGN APPROACH

A. Functional Configuration

As noted in Figure 2, a number of signals flow between the OCU and MBU. The functional signal flow through hardware is more complicated. Figure 6 depicts the hardware layout allowing the depicted signal flow of Figure 2.

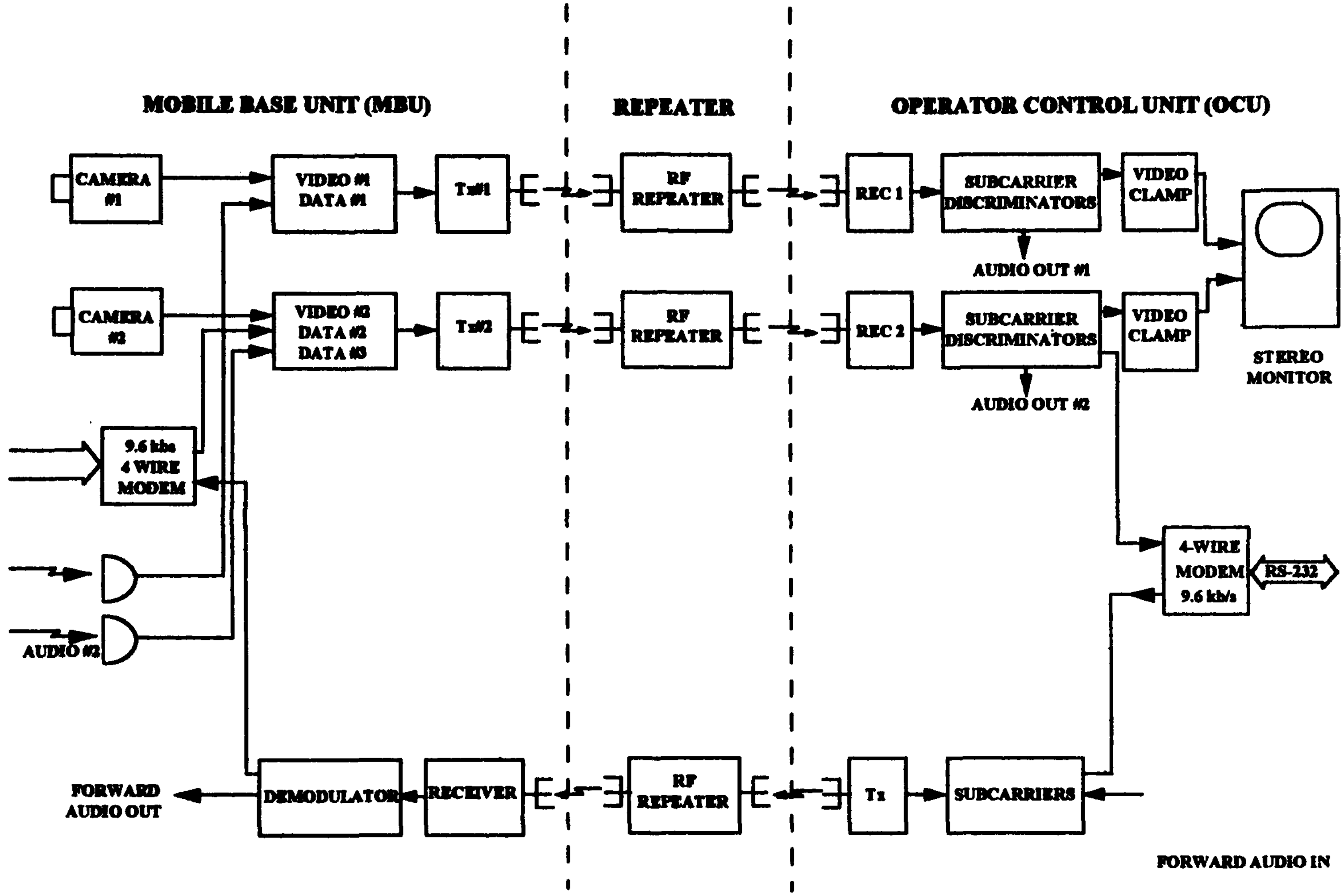


Figure 6. Data Link Block Diagram

At each vehicle terminal of the data link the physical location of the hardware differs slightly. The physical layout at the OCU is to mount all communication components on a circular plate of approximately three feet in diameter on the roof of the HMMWV. The MBU components are mounted on a rectangular plate located behind the driving camera mast. Antennas mounted on each plate are 1/4 wavelength stubs with a smooth plastic cover for protection and are about two inches high. Figure 7 shows the data link mounting location for the MBU terminal.

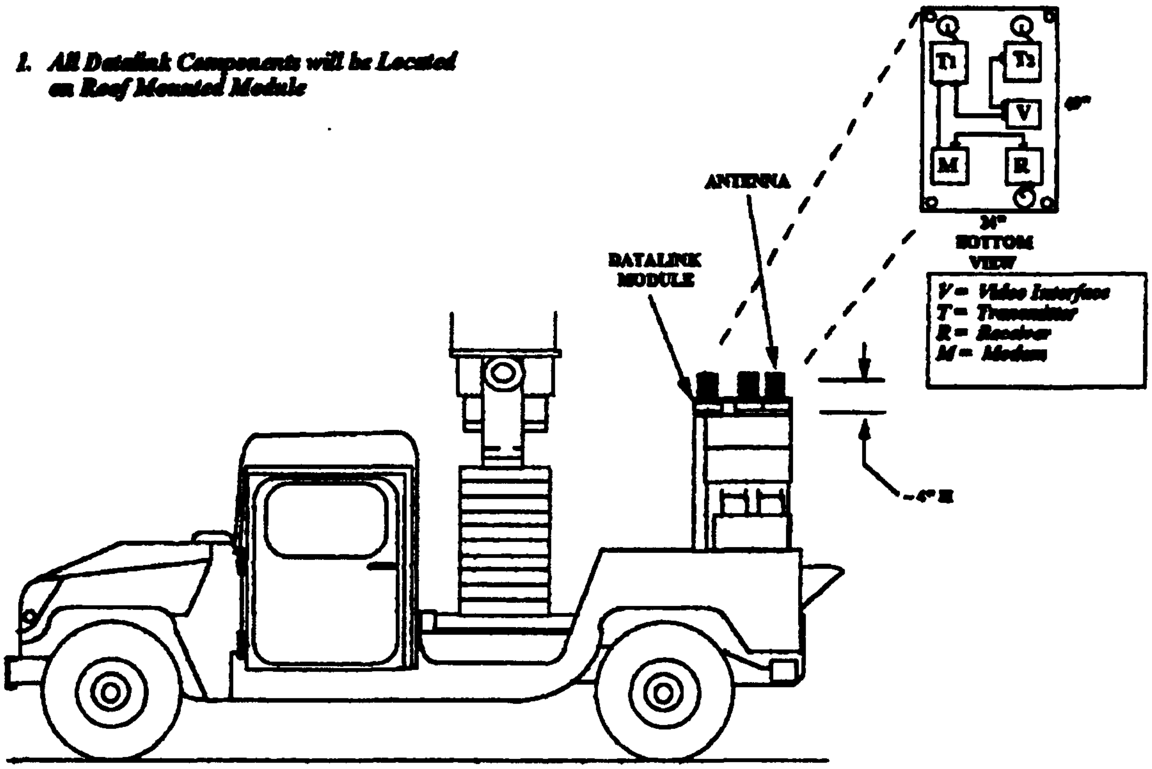


Figure 7. MBU Data Link Location

The physical hardware layout of the data link terminals at the OCU and MBU differ slightly. Figure 8 depicts the component layout of the MBU terminal, and Figure 9 depicts the component layout of the OCU terminal. All receivers, transmitters, modems and related components of the data link for each vehicle will have individual power control relays. Each terminal will be controlled via a 1553 bus controller. Additionally, the controller will monitor the receiver signal levels allowing the vehicle computer to anticipate possible loss in signal and to take corrective action before catastrophic loss of contact. The power relays will permit putting the vehicle in a sleep mode for power conservation. Both the MBU and OCU terminal will operate using 28 Vdc power.

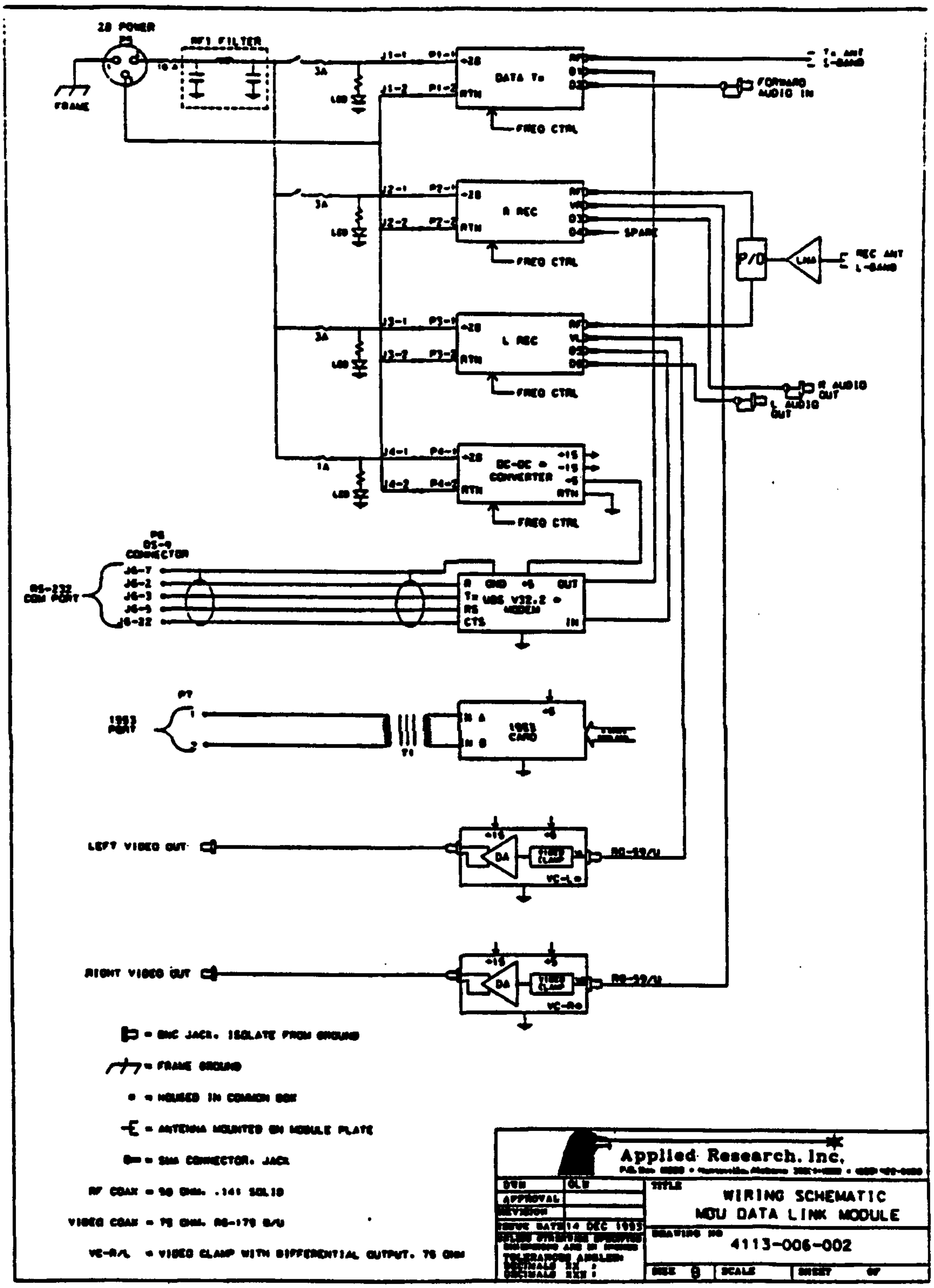


Figure 8. MBU Hardware Layout

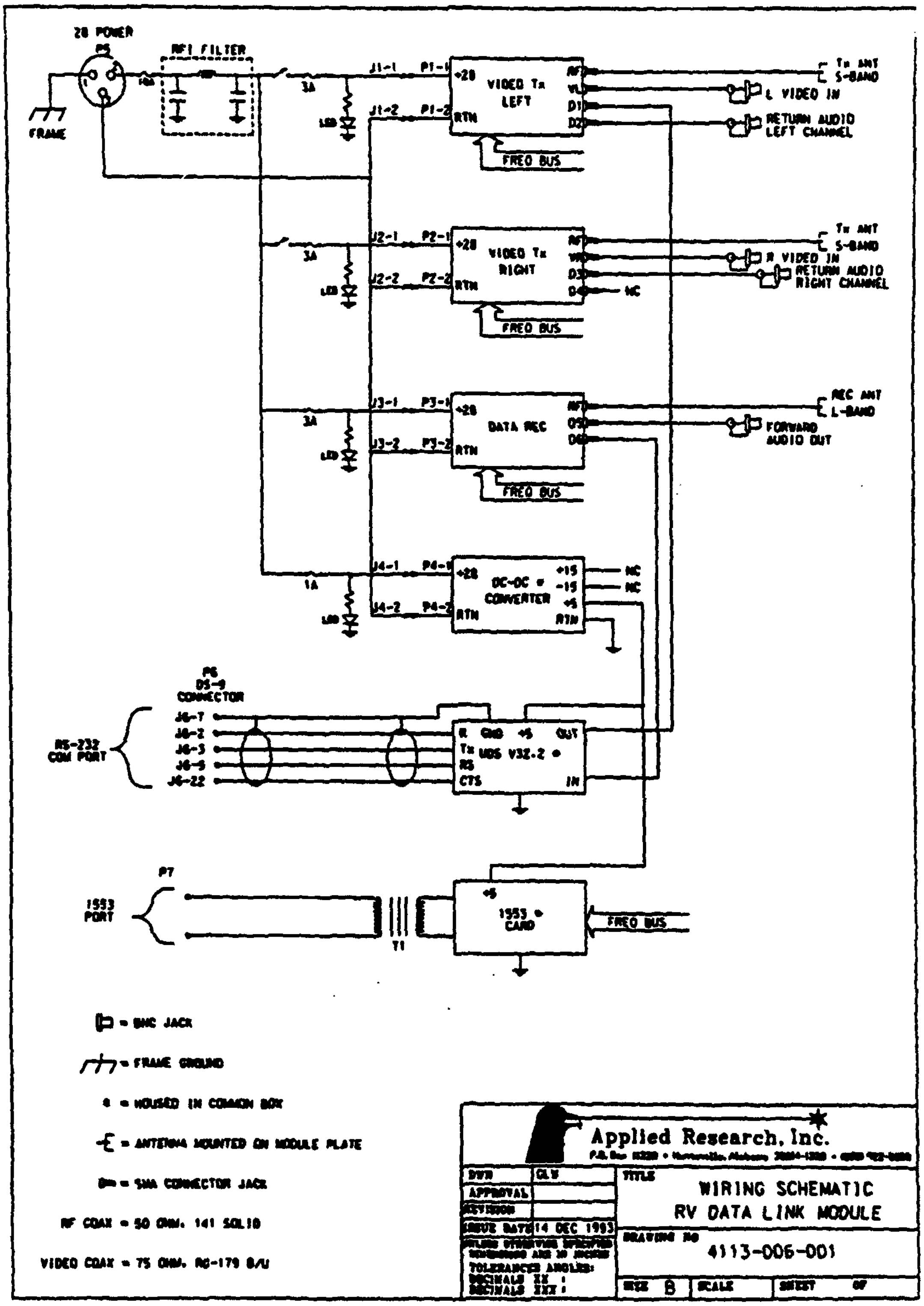


Figure 9. OCU Hardware Layout

The repeater will use radio transmitters of similar configuration to the vehicle radios. The antenna are more complex, providing a horizontal gain of about 10 to 12 dB. Two types of antennas are under consideration. A stacked vertical array, approximately 5 feet high or a discone antenna of about 4 feet diameter and 12 inch high. The azimuth beam of both antennas will be 360 degrees, making it possible for vehicles to operate in any direction from the repeater. Specialized antennas may be required if vehicles are operated in obscured areas or at extended range. Usable gains for the UGV antennas are:

OCU and MBU stub antenna	+ 3 dBi
Repeater antenna	+ 7 dBi

The relay will be configured for AC power operation.

B. Recommended Hardware

The selected system will use missile grade hardware. Missile grade hardware is defined as small high performance transmitters and receivers of robust design for a missile test environment. Units of this type are manufactured by several vendors and provide reliable test range performance. Estimated power, weight, size and cost of systems meeting the design are summarized in Table 3.

Table 3. Missile Grade Hardware Recommended

RF Sub System	Power	Weight	Size	Unit Cost	Total Cost
MBU Communication Assembly					
2 ea. Video Transmitter	2(33 W)	2(.9 lb)	3.5 x 2.5 x 1.5	$5.8K	$11.6K
1 ea. Data Receiver	16 W	1.2 lb	5.0 x 3.0 x 1.5	$6.4K	$6.4K
1 ea. Modem (4 wire)	10 W	1.0 lb.	7.0 x 4.5 x 1.7	$1.0K	$1.0K
3 ea. Antenna		3(.7 lb)	2 H x 1.5 D	$1.5K	$4.5K
Subsystem Total	92 W	6.1 lb		$23.5K	
Repeater Assembly					
3 ea. Rec/Tx NDR Assembly	3(49 W)	3(2.3 lb)	3.5 x 5.0 x 1.5	$11.2K	$33.6K
3 ea. Low Noise Amplifiers	2(5 W)	2(.5 lb)	2 x 3 x 1.2	$0.5	$1.5K
3 ea. RF Filters		2(1.1 lb)	6 x 12 x 3	$1.5K	$4.5K
6 ea. Antenna		6(2 lb)	12 dia.	$1.5K	$1.5K
	157 W	22.1 lb			$48.6K
OCU Assembly					
2 ea. Video Receivers	3(16 W)	2(1.2 lb)	5.0 x 3.0 x 1.5	$6.4K	$12.8K
1 ea. Data Transmitter	33 W	.9 lb	3.5 x 2.5 x 1.5	$5.4K	$5.4K
1 ea. Modem (4 wire)	10 W	1 lb	7.0 x 4.5 x 1.7	$1.0K	$1.0K
3 ea. Antenna		3(.7 lb)	2 H x 1.5 D	$1.5K	$4.5K
	75 W	6.4 lb		$23.7K	
Total for electronics components				$95.8K	$95.8K

Note: Cost, weight, and size for hardware is a composite from information supplied from several vendors.

IV. LINK PERFORMANCE

The performance of the RF data link can be estimated. By calculating the S/N values for the received signal at the receiver a signal margin can be developed. Signal margin is defined as the dB difference between the actual received signal and the minimum expected signal.

For the UGV TTB there are two types of signals to deal with, video, and command/ telemetry data. Typically, the video links have the poorest signal margins. Video requires a 20 MHz bandwidth, where the data channels require a 1 MHz bands. This difference means that the data channel has a 13 dB advantage even before factoring in the lesser S/N required for a quality digital channel. This will give the serial data channel a significant safety margin in controlling the vehicle even after the video link is lost in noise.

The RF carrier to noise is calculated using the equation:

$$CN = \frac{P_t * G_t * G_r * \lambda^2}{(4 * \pi)^2 * R^2 * L * k * T_n * B_n} \qquad (4)$$

These parameters are used as defined in Table 4.

Table 4. Baseline RF System Parameters

Transmitter power, P_t	5 Watts
MBU antenna gain, G_t	+3 dB
Repeater antenna gain, G_r	+7 dB
Cable loss, L	2 dB
System noise temperature, T_o	516.6 degrees K
RF bandwidth, B_n	20 MHz
Range	1.6, 6, and 10 km
Frequency	1720 to 2380 MHz

The baseline RF Carrier to Noise (CN) ratio is calculated for the video channel using the conditions listed in Table 4. Figure 10 shows the baseline CN value plots, using these parameters, as a function of frequency for ranges of 1.6, 6 and 10 kilometers. The range of 1.6 km is typical of the Redstone Arsenal UGV TA–5 test area. The 6 kilometer range is the program requirement, and 10 kilometers is the goal. The demodulated video S/N will be substantially greater due to the FM improvement factor.

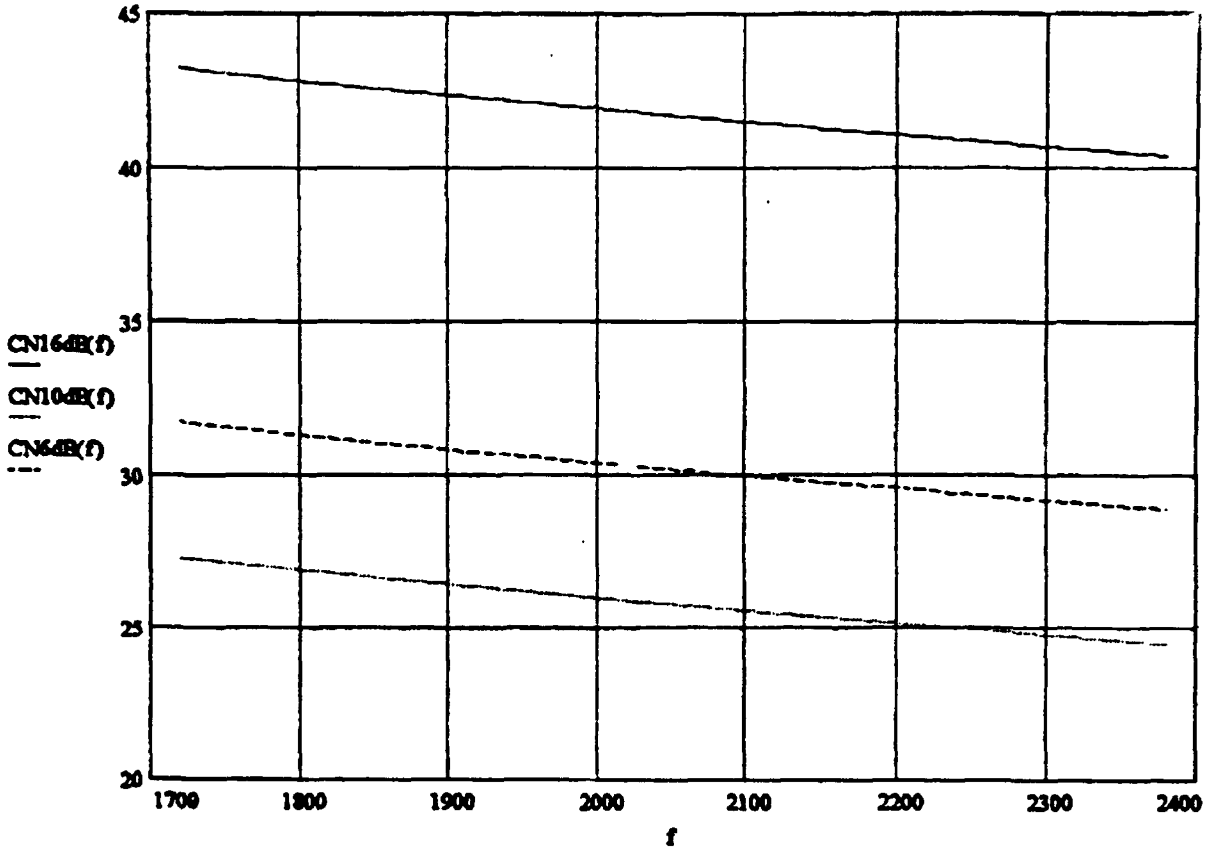


Figure 10. Received Video Carrier to Noise of the MBU/OCU at the Repeater as a Function of Frequency for Ranges of 1.6, 6, and 10 km

The RF CN for the forward narrow bandwidth data channel is calculated and shown in Figure 11. Conditions are the same as for the video channel (above) except the bandwidth has been reduced to 1 MHz. Demodulated S/N estimates with available signal margin for the video and data channels are tabulated in Table 5.

Table 5. Calculated SN Values for Video, Audio, and Data Transmission Over Various Ranges

Range 10 km									
Video							Audio		
	Freq	RF	CN	SNv	Std	Margin	SNa	Std	Margin
MBU to RS	1720	–72.2	26.3	47.2	41	+6.2	53.8	60	–6.2
MBU to RS	1780	–72.4	25.9	46.9	41	+5.9	53.5	60	–6.5
RS to OCU	2320	–74.7	23.6	44.6	41	+3.6	51.2	60	–8.8
RS to OCU	2380	–74.9	23.5	44.4	41	+3.4	51.0	60	–9.0
Range 1.6 km									
Video							Audio		
	Freq	RF	CN	SNv	Std	Margin	SNa	Std	Margin
MBU to RS	1720	–56.2	42.2	63.1	41	+22.2	69.7	60	+9.7
MBU to RS	1780	–56.5	49.9	62.8	41	+21.8	69.4	60	+9.4
RS to OCU	2320	–58.8	39.6	60.5	41	+19.5	67.1	60	+7.1
RS to OCU	2380	–59.0	39.3	60.3	41	+19.3	66.9	60	+6.9
Range 10 km, (serial digital data)									
Digital Data							Audio		
	Freq	RF	CN	SNd	Std	Margin	SNa	Std	Margin*
OCU to RS	1835	–72.7	38.7	52.4	13.2	+39.2	61.7	60	+1.7

* Margin shown for the audio channel is based on 100 kHz bandwidth. A 20 kHz low pass filter will improve the audio S/N by 7 dB. A constant data/audio 100 kHz bandwidth is used for simplicity of design.

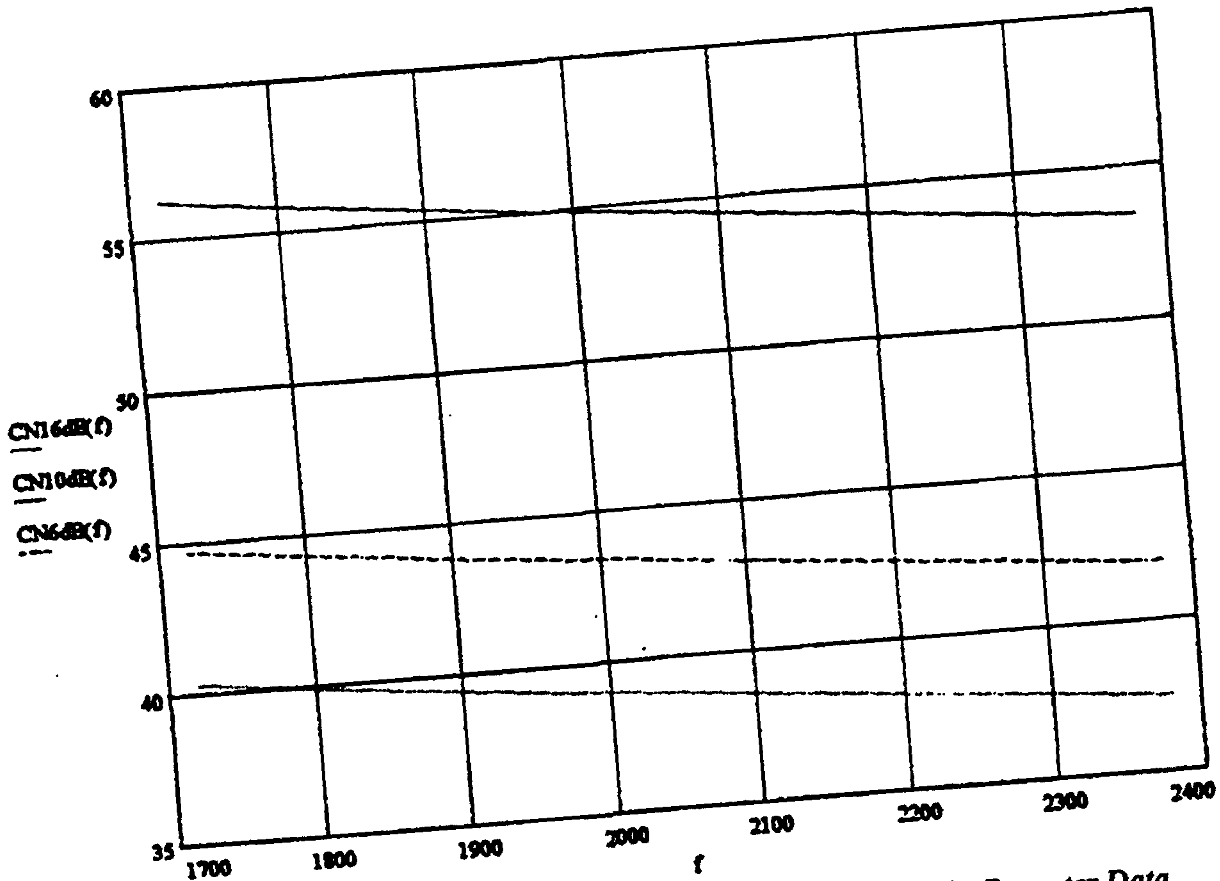


Figure 11. Received Data Carrier to Noise of the MBU/OCU at the Repeater Data as a Function of Frequency for Ranges of 1.6, 6, and 10 km

A. System Temperature Computation

The temperature of the receiver assembly in a communications link impacts performance significantly. The computation of the system temperature, T_S, must accurately account for all subelements to be included in the receiver. The system temperature is calculated using the Equation (5)

$$T_s = \alpha * T_a + T_l * (1 - \alpha) + T_{na} + \frac{T_r}{G_{na}} \tag{5}$$

Table 6 defines the variables and values used to determine T_S for the UGV TTB data link. Using Equation (5), the system noise temperature is calculated to be 411.581 degrees K. This varies from the value of 516.6 degrees K used previously in that 516.6 represents a worst case value. The difference in T_S values increase the results shown in Table 5 by 1 dB if T_S = 411.581 is used instead.

Table 6. System Temperature Variables

α	0.708	Transmission line loss power ratio
T_a	290 deg. K	Antenna temperature
T_l	290 deg. K	Transmission line temperature
T_{pa}	120 deg. K	Pre–amplifier temperature
T_r	500 deg. K	Receiver or second stage temperature
G_{pa}	25 dB	Pre–amplifier gain
L	1.5 dB	Transmission line loss

B. Received Carrier to Noise and Signal to Noise Computation

The RF carrier to noise is calculated using Equation (4):

$$CN = \frac{P_t * G_t * G_r * \lambda^2}{(4 * \pi)^2 * R^2 * L * k * T_n * B_n}$$

Table 7 lists the parameters used in calculating CN. These values were used in producing the plots of Figures 10 and 11 and the data of Table 5. The baseline CN calculated using these values is 24.507 dB.

Table 7. Carrier to Noise Calculation Parameters

P_t	5 W	Transmitter Power
G_t	3 dB	Transmitter antenna gain
G_r	7 dB	Receiver antenna gain
f	2380 MHz	frequency
B_n	20 MHz	bandwidth
R	10 km	range
k	1.38×10^{-23}	Boltzmann's constant

The next step in determining the system signal to noise is to determine the receiver noise floor (NR). This is established by:

$$NR = 10 \log(k * T_S * B_n) + 30 \qquad (6)$$

where the factor of 30 added to NR converts the value to dB referenced to a milliwatt (dBm). Using the values defined in Table 7 the calculated receiver noise floor is – 99.446 dBm.

The received S/N level is calculated by:

$$S/N = CN + NR \qquad (7)$$

which is determined to be: S/N = 24.507 + –99.446 = – 74.939 dBm.

For an FM video transmission system, there are several improvements to the video signal that are added. These include FM modulation improvement, pre–emphasis/de–emphasis, and from converting RMS data to P–P video/RMS noise. The FM improvements requires that the receiver operate above the threshold, typically at 12 dB CN. Table 8 provides the variables and values used in calculating the improvements to the video Signal to Noise (SNv).

Table 8. Video Signal to Noise Variables

CN	24.507 dB	Carrier to noise
f_p	4 MHz	peak composite deviation video
f_m	8.6 MHz	highest baseband frequency (including subcarriers)
B_v	4 MHz	video bandwidth
B_{if}	20 MHz	IF bandwidth
W	12.8 dB	CCIR 525 line emphasis weighting factor
CF	6 dB	RMS to P–P luminance conversion factor

Equation (8) is the video modulation index and Equation (9) is the video signal to noise improvement.

$$\beta_v = \frac{f_p}{B_v} = \frac{4}{4} = 1 \tag{8}$$

$$SN_v = CN + 10\log\left[3 * \left(\frac{f_p}{f_m}\right)^2\right] + 10\log\left(\frac{B_{if}}{2 * B_v}\right) + W + CF \tag{9}$$

Using the values of Table 8 with Equations (8) and (9) the calculated SNv is 45.822 dB.

C. Signal to Noise for Data (SN_d) Subcarriers

The SN_d is calculated in a similar manner as that of the video signal. The modulated data consist of both digital and audio data. Equations (8) and (9) are modified for the appropriate case and the variables changed for each case are noted in Table 9. The modified equations become:

$$\beta_S = \frac{\Delta F}{f_{sc}} = \frac{4}{8.2} = 0.488 \tag{10}$$

$$CN_{sc} = CN + 10\log\left(\frac{B_{if}}{2 * B_{sc}}\right) + 10\log\left(\frac{\Delta F}{f_{sc}}\right)^2 \tag{11}$$

for digital data, and

$$\beta_S = \frac{\Delta F_c}{f_{mc}} = \frac{0.1}{0.1} = 1 \tag{12}$$

$$SN_a = CN_{sc} + 10\log\left(\frac{B_{sc}}{2 * B_a}\right) + 10\log\left[3 * \left(\frac{\Delta F_c}{f_{mc}}\right)^2\right] + E \tag{13}$$

for the audio data.

Calculated values yield CNsc = 32.251 dB and SNa = 52.032 dB.

Table 9. Subcarrier Modulation Parameters

Data Subcarrier Variables		
ΔF	4 MHz	Peak deviation of carrier by subcarrier
f_{sc}	8.2 MHz	Subcarrier frequency
B_{sc}	0.4 MHz	Subcarrier pre–detection noise bandwidth
Subcarrier Data Signal to Noise Variables		
B_a	0.1 MHz	Audio post detection bandwidth
f_{mc}	0.1 MHz	Highest audio modulation frequency
E	12 dB	Audio pre/de–emphasis improvement factor, 75 µs
ΔF_c	0.1 MHz	Subcarrier peak deviation

V. OPERATIONS PERFORMANCE

In general, operation of the radio data link is automatic. Input/output of video and audio data will be transparent to the user. From S/N estimates there should be no visual noise in the television signals for operation at Redstone Arsenal where maximum range between OCU/MBU to repeater will not exceed 10 km. At the maximum range a very minor degradation of video may begin to be observed. The return high quality audio S/N will degrade slightly to approximate 45 dB, which is still within the definition of excellent quality video. The limitation on range can be easily improved with additional antenna gain at the repeater using fixed position dish antennas. Such an antenna would require a positioning system or limit the operating area of the vehicles.

A. Operating Modes

The UGV TTB has three operational modes in with communications between vehicles are feasible. These are described below. Mode 1 is planned to be implemented by the data link configuration described by this report. Mode 2 is available with modification of the equipment described in this report. Mode 3 uses a separate communication media. Control of mode utilized is chosen from the OCU.

1. Mode 1: Relayed MBU to OCU Communications

This mode, as described by this report, will use a repeater between the MBU and OCU. It will provide a most reliable link. It is the recommended radio link.

2. Mode 2: Direct MBU to OCU Communications

This mode bypasses the repeater and allows direct vehicle to vehicle communications. It requires the system operating frequencies at either the OCU or MBU be changed. This will require replacement of both receiver and transmitter at one vehicle terminal since the frequency bands are different. Severe multipath may be experienced in this mode, since both vehicle antennas are close to the ground. Mode 2 is not recommended.

3. Mode 3: Fiber Optic Communications

This mode uses fiber optics transmitters and receivers with interconnecting fiber optic cables. Performance will be equal to the Mode 1 radio link and should be immune to external noise and multipath. This mode is implemented on the TTB system, but is external to the RF data link.

B. Growth Operational Modes

1. Interface to Airborne Relay

An airborne relay provides more flexibility of communications that ground based relays. For a tactical situation an airborne relay relieves the logistics of establishing a fixed relay and provides more flexibility in providing maneuverability of a UGV. Potential relay could be accomplished utilizing a system such as the Unmanned Air Vehicle or a geosynchronous satellite as the relay vehicle.

2. Digital Data Link

A second generation UGV digital radio link is strongly recommended for future robotic control. Use of image compression and digital modulation together with specialized satellites for relay are now realizable. Low profile high gain phased array antennas suitable for HMMWV roof mounting are feasible that will provide the gain necessary for high altitude repeaters.

3. Extended Ground Relay Range

Extended range performance of the UGV data link is entirely feasible. Range is limited using a single repeater to approximately 10 km depending upon terrain. Range extension of LOS conditions are entirely possible, requiring only modest increase of antenna gain and/or increase in RF power level. For example, changing the power from 5 W to 20 W will increase the range to 20 km, the same can be accomplished with a 6 dB gain increase at the repeater, a more cost effective solution. Increased antenna gain through the use of directional antenna assemblies would require an antenna positioner.

A second means of increasing operating range would be through the use of multiple repeater sites. The use of several sites would permit better RF coverage of an area to avoid problems associated with loss of LOS in terrain having significant variations in contour. A multi–relay assembly could be configured to work in much the same manner as commercial mobile telephones currently work.

VI. CONCLUSIONS

This report has described the design requirements, tradeoffs, and hardware approach for the Technology Test Bed Demonstration Program radio frequency data link to provide command/control to and imagery/status reporting from an unmanned ground vehicle. The system described is under development with laboratory and field evaluation planned over the next six to eight months from the date of this report. The performance projections described here are expected to be validated and results reported in a subsequent report.

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